Study of the transverse momentum distribution of transport models of kaon, Pion, and (anti-)proton production in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV

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Abstract

In this study, the transverse momentum spectra of $k^{\pm}$, $\pi^{\pm}$ and $p(\bar{p})$ particles in mid-rapidity ($|y| < 0.1$) for nine centrality classes are investigated in $^{238}U+^{238}U$ collisions at $\sqrt{s_{NN}}$=193 GeV within the cascade and soft momentum-dependent equation of state (SM-EoS) mode of the UrQMD model. Other extracted observable from p_T spectrum includes average transverse momentum ($\langle p_T \rangle$), the yield (dN/dy) as well as the ratio of particle type are also shown in function of collision centrality. It is found that the U+U collision process is subregional without considering the deformation of U nucleus. Before the collision centrality is $50-60\%$, the experimental data are described well using cascade mode when the $p_T < 1.2 GeV/c$. The results are in good agreement with the experimental data using the SM-EoS mode at $p_T > 1.2 GeV/c$. For the case of $60-80\%$ centrality, the SM-EoS mode describes the data better. At RHIC energy, it is also found that pair production is the dominant production mechanism for particles, with the anti-ion to ion yield ratio suggesting.

PACS numbers: 24.10.Lx, 25.75.Dw, 25.75.-q

Keywords: UrQMD model; cascade; SM-EoS; transverse momentum distributions; U+U collisions

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I. INTRODUCTION

Heavy-ion collisions (HICs) at ultra-relativistic energies present a unique opportunity to study properties of strongly interacting matter at extreme temperatures and densities [1–7]. Understanding the mechanisms of particles and fragment generation in super-relativistic HICs is important because it may provide information about the phase transition of quantum chromodynamics (QCD) from quark- gluon plasma (QGP) to hadron gas (HG) [8, 9]. Over the past two decades, many experiments have been conducted at the Relativistic Heavy Ion Collider (RHIC) near the critical energy of the hadronic matter to QGP phase transition. [10]. Theoretical studies on particle and antiparticle generation have been carried out for many years, such as statistical model, coalescence model and transport model [11–19]. The investigation of transport phenomena is particularly crucial in comprehending numerous fundamental properties [20]. One of the reasons to study transverse momentum spectra of particles produced in high-energy collisions is their ability to provide critical information about the frozen state of the dynamics of interacting systems [21]. At the Relativistic Heavy Ion Collider (RHIC), experiments have demonstrated that in U+U collisions with a center of mass energy of 193 GeV, a highly dense system of defined quarks and gluons forms, creating a very hot and dense medium [22].

The ultra-relativistic quantum molecular dynamics (UrQMD) method is utilized to generate the transverse momentum distributions of π mesons, kaons, and $p(\bar{p})$ particles in U+U collisions at a center-of-mass energy of 193 GeV. The study also considers the presence of collisional interactions between particles. Comparisons are made with experimental data collected by the STAR Collaboration [23]. The primary objective of this research is to obtain information about the behavior of nuclear reactions that could be used to understand the final state particle production in U+U collisions at the RHIC energy.

II. ULTRARELATIVISTIC QUANTUM MOLECULAR DYNAMICS TRANSPORT MODEL

A. The ultra-relativistic quantum molecular dynamics (UrQMD) model

The UrQMD model is a microscopic many-body approach to transport that can be applied to study the interactions of protons with protons (pp), with protons on a nucleus (pA)

with a nucleus on a nucleus (AA) over the energy range from the Spheron Ion Source to the Large Hadron Collider. This model is based on the propagation of color strings, of which the constituent quarks and diquarks (as the end of the string) carry mesonic and baryonic degrees of freedom [24]. It can combine different reaction mechanisms and provide theoretical simulations of various experimental observations. Currently, in our model, subhadrons' degrees of freedom enter through a formation time for hadrons resulting from string fragmentation, which is dominant at the early stages of heavy-ion collisions (HICs) at high SPS and RHIC energies [25–27].

Like the quantum molecular dynamics (QMD) model, the UrQMD model follows parallel principles to simulate hadrons in phase space with the propagation of each individual hadron's phase space according to Hamilton's equation of motion [28],

$$\dot{\vec{r_i}} = \frac{\partial H}{\partial \vec{p_i}}, \qquad \dot{\vec{p_i}} = -\frac{\partial H}{\partial \vec{r_i}}. \tag{1}$$

Here, $\vec{r_i}$ and $\vec{p_i}$ are the coordinate and momentum of the hadron i, and the Hamiltonian H consists of the kinetic energy T and the effective interaction potential energy U,

$$H = T + U. \tag{2}$$

This microscopic transport approach simulates the interactions of incoming and newly produced particles, the excitation and fragmentation of color strings and the formation and decay of hadronic resonances. In the pursuit of higher energies, it is crucial to consider the treatment of subhadronic degrees of freedom. In this current version, the degrees of freedom are introduced through a hadron formation time, in the string fragmentation process, and there is no explicit incorporation of a phase transition from a hadronic to a quark-gluon phase in the model's dynamics. However, a detailed analysis of the model in thermal equilibrium yields an effective equation of state of the Hagedorn type [29].

B. The soft momentum dependent equation of state (SM-EoS)

In the standard framework of the UrQMD model, the term "potential energy" incorporates various types of interactions such as those involving the two-body and three-body Skyrme-, Yukawa-, Coulomb- and Pauli-terms [16, 28, 30],

$$U = U^{(2)}_{\text{sky}} + U^{(3)}_{\text{sky}} + U_{\text{Yuk}} + U_{\text{Cou}} + U_{\text{pau}}. \tag{3}$$

In the upgraded UrQMD (version 3.4) of the present work, additional terms are defined: (1) the density-dependent symmetry potential term U_{sym} and (2) the momentum-dependent term U_{md} [31]. In this study, the soft momentum-dependent (SM) equation of state (EoS) is applied, which is presented in Ref. [32]. In the RHIC energy regime, the Yukawa-, Pauli-, and baryon symmetry potentials become unimportant, while the Skyrme and momentum-dependence parts of potentials still affect the full HIC dynamic process [33]. During the formation time, the "pre-formed" particles (string fragments that will be abducted onto hadronic states later on) are usually treated to be free streaming, while reduced cross sections are only included for leading hadrons.

In this paper, the transverse momentum distributions and central yields of π mesons, k mesons and $p(\bar{p})$ generated in U+U collisions at $\sqrt{s_{NN}}$=193 GeV at mid-rapidity ($|y|$<0.1) are studied by using UrQMD cascade mode and SM-EoS mode.

III. RESULTS AND DISCUSSIONS

A. Transverse momentum spectrum

Fig. 1 and Fig. 2 are shown the transverse momeutum spectra in nine centrality classes in U+U collisions at $\sqrt{s_{NN}}$=193 GeV at mid-rapidity ($|y|$<0.1) for π^+ and π^-. There are nine centrality classes, representing a range of $0-5\%$, $5-10\%$, $10-20\%$, $20-30\%$, $30-40\%$, $40-50\%$, $50-60\%$, $60-70\%$ and $70-80\%$ respectively. The dotted lines are the results calculated from the cascade mode of UrQMD model. The solid lines are the results calculated from the soft momentum dependent equation of state mode of UrQMD model. The symbols are the experimental data from the STAR Collaboration [23]. The calculations are shown for $p_T < 2.0GeV/c$ in the Figure (a) and (b). Figure (c) shows the results of the calculation for $p_T < 1.2GeV/c$ taking into account the same systematic uncertainties as the experiment . The UrQMD model's cascading mode has been observed to exhibit remarkable agreement with empirical laws before $50-60\%$ centrality. But the yield is higher than the experimental values in the central transverse momentum region. At $60-80\%$ centrality, the SM-EoS mode can better describe the experimental results. When the uncertainty of the system is considered, the agreement with the experiment is better in Figure (c). In the region with $1.2GeV/c < p_T < 2.0GeV/c$, the cascade model can well

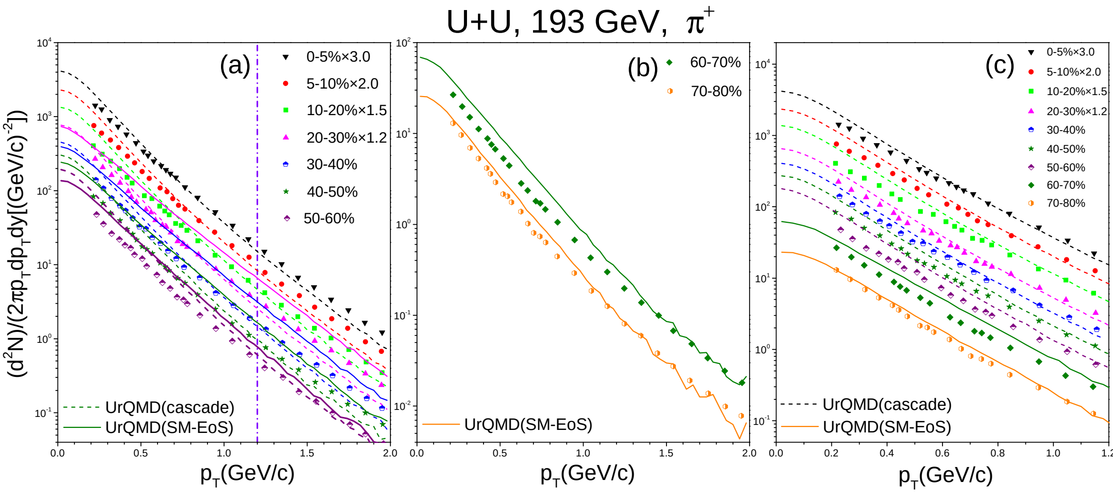

FIG. 1: Transverse momentum spectra of π^+ are calculated at mid-rapidity ($|y| < 0.1$) in U+U collisions at $\sqrt{s_{NN}}$=193 GeV for $0-5\%$, $5-10\%$, $10-20\%$, $20-30\%$, $30-40\%$, $40-50\%$, $50-60\%$, $60-70\%$ and $70-80\%$ centralities from the cascade mode and the soft momentum dependent equation of state mode of UrQMD model. The lines denote calculations, while the symbol represents experimental data taken from the STAR Collaboration [23].

describe the experimental data.

Fig. 3 and Fig. 4 are shown the transverse momeutum spectra in nine centrality classes in U+U collisions at $\sqrt{s_{NN}}$=193 GeV at mid-rapidity ($|y|$<0.1) for k^+ and k^-. The dotted lines are the results calculated from the cascade mode of UrQMD model. The solid lines are the results calculated from the soft momentum dependent equation of state mode of UrQMD model. The symbols are the experimental data from the STAR Collaboration [23]. The calculations are shown for $p_T < 2.0GeV/c$ in the Figure (a) and (b). Figure (c) shows the results of the calculation for $p_T < 1.2GeV/c$ taking into account the same systematic uncertainties as the experiment. It can be found that the SM-EoS mode of UrQMD model can describe the overall change trend well, but it is about 1.6 times larger than the experimental result before $50-60\%$ centrality in the region with $p_T < 1.2GeV/c$. With the increase of collision centrality, in the region with $p_T > 1.2GeV/c$, the theoretical results are more and more consistent with the experimental results. At $60-80\%$ centrality,

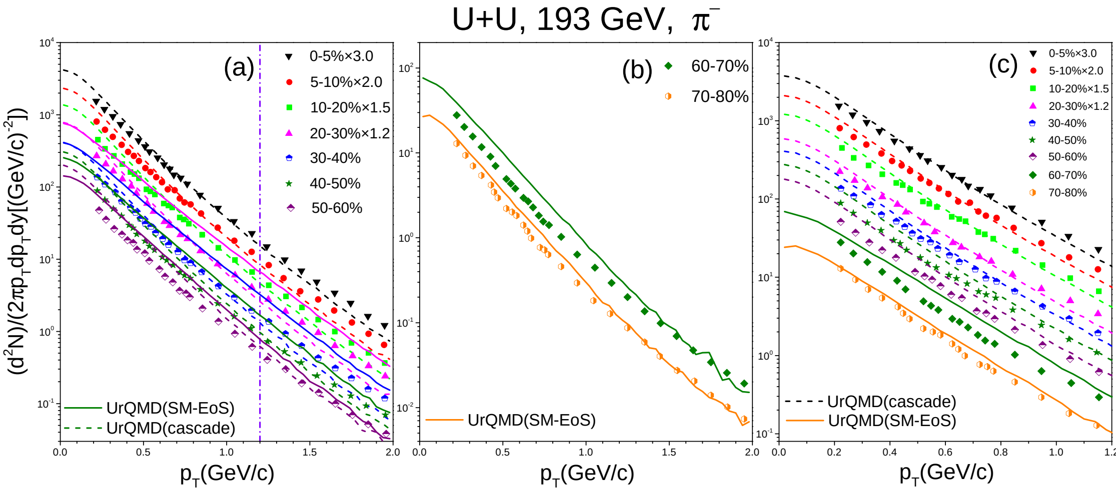

FIG. 2: Transverse momentum spectra of π^- are calculated at mid-rapidity ($|y| < 0.1$) in U+U collisions at $\sqrt{s_{NN}}$=193 GeV for $0-5\%$, $5-10\%$, $10-20\%$, $20-30\%$, $30-40\%$, $40-50\%$, $50-60\%$, $60-70\%$ and $70-80\%$ centralities from the cascade mode and the soft momentum dependent equation of state mode of UrQMD model. The lines denote calculations, while the symbol represents experimental data taken from the STAR Collaboration [23].

the SM-EoS mode can better describe the experimental results. When the uncertainty of the system is considered, the yield is higher than the experimental values in the central transverse momentum region in Figure (c).

Fig. 5 and Fig. 6 are shown the transverse momeutum spectra in nine centrality classes in U+U collisions at $\sqrt{s_{NN}}$=193 GeV at mid-rapidity ($|y|$<0.1) for p and $\bar{p}$. The dotted lines are the results calculated from the cascade mode of UrQMD model. The solid lines are results obtained from the UrQMD model using a soft momentum dependent equation of state mode. The symbols are the experimental data from the STAR Collaboration [23]. The calculations are shown for $p_T < 2.0GeV/c$ in the Figure (a) and (b). Figure (c) shows the results of the calculation for $p_T < 1.2GeV/c$ taking into account the same systematic uncertainties as the experiment. We conclude that the UrQMD model's cascade mode can reproduce the experimental data very well for $p_T < 1.2GeV/c$, and the simulation results are in good agreement with the experimental data under SM-EoS mode in the region with

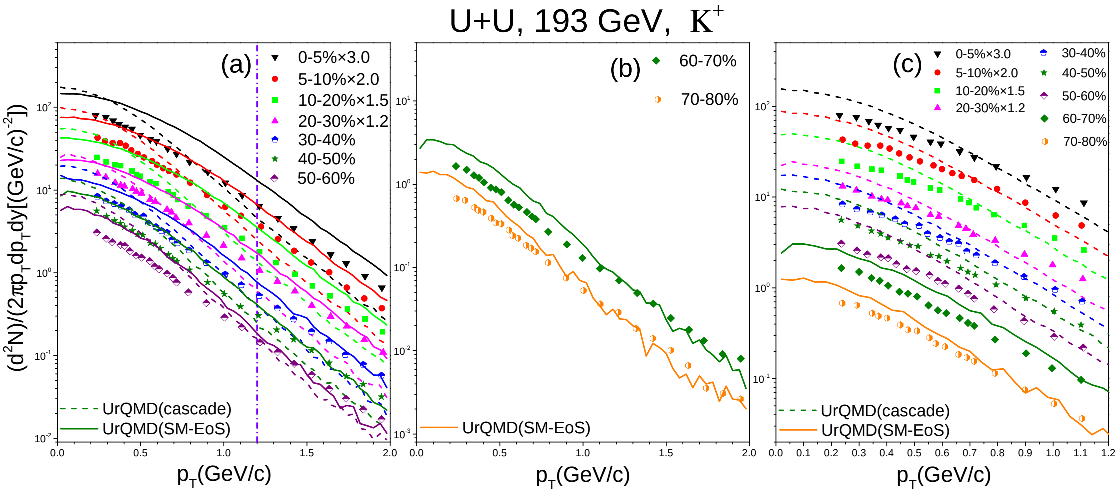

FIG. 3: Transverse momentum spectra of k^+ are calculated at mid-rapidity ($|y| < 0.1$) in U+U collisions at $\sqrt{s_{NN}}$=193 GeV for $0-5\%$, $5-10\%$, $10-20\%$, $20-30\%$, $30-40\%$, $40-50\%$, $50-60\%$, $60-70\%$ and $70-80\%$ centralities from the cascade mode and the soft momentum dependent equation of state mode of UrQMD model. The lines denote calculations, while the symbol represents experimental data taken from the STAR Collaboration [23].

$1.2GeV/c < p_T < 2.0GeV/c$ before $50-60\%$ centrality. With the increase of collision centrality, in the region with $p_T > 1.2GeV/c$, the theoretical results are more and more consistent with the experimental results. At $60-80\%$ centrality, the SM-EoS mode can better describe the experimental results. When the uncertainty of the system is considered, the yield is in good agreement with the experimental data in Figure (c).

In general, in the area of $p_T < 1.2GeV/c$, the cascade mode can better describe the experimental results. In the $1.2GeV/c < p_T < 2.0GeV/c$ region, the SM-EoS model can better describe the experimental results. Here we describe the collision process of U+U in a piecewise way, because the Uranium nucleus is ellipsoidal, but we do not consider its deformation characteristics in the actual calculation, and think that the collision probability of the tip-tip, body-body and body-tip is the same. We will analyze the impact of the deformation in more detail in the future. As can be seen from Figure 1-6, the energy density in the central region is relatively large at the initial stage of collision, and the particles generated cannot fly away from the central region quickly, and they deposit part or all of

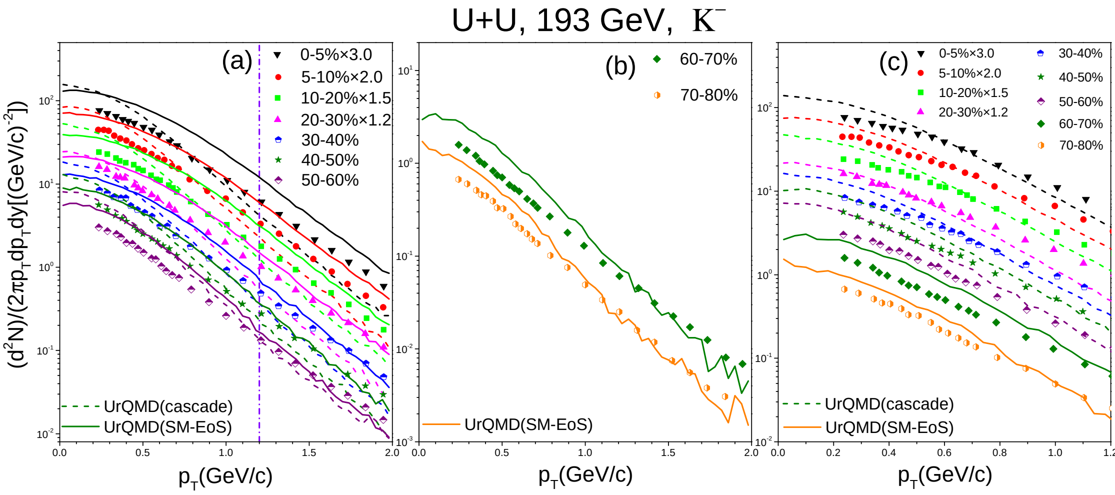

FIG. 4: Transverse momentum spectra of k^- are calculated at mid-rapidity ($|y| < 0.1$) in U+U collisions at $\sqrt{s_{NN}}$=193 GeV for $0-5\%$, $5-10\%$, $10-20\%$, $20-30\%$, $30-40\%$, $40-50\%$, $50-60\%$, $60-70\%$ and $70-80\%$ centralities from the cascade mode and the soft momentum dependent equation of state mode of UrQMD model. The lines denote calculations, while the symbol represents experimental data taken from the STAR Collaboration [23].

their energy in the central region, so the effect of the equation of state is not important. As time goes on, the previously created particles interact with other nucleons and continue to fly away from the central region, so the influence of the average field becomes greater and greater.

B. Average transverse momentum distributions

Figure 7 shows the variation of$\langle p_T \rangle$ with $\langle N_{part} \rangle$ at midrapidity ($|y| < 0.1$) for π^+, k^+ and p particles in U+U collisions at $\sqrt{s_{NN}}$=193 GeV. The black diamonds were obtained from UrQMD calculations, and the red solid circles are the experimental data [23]. It is found that the experimental results can be described within the tolerance of error. The values of $\langle p_T \rangle$

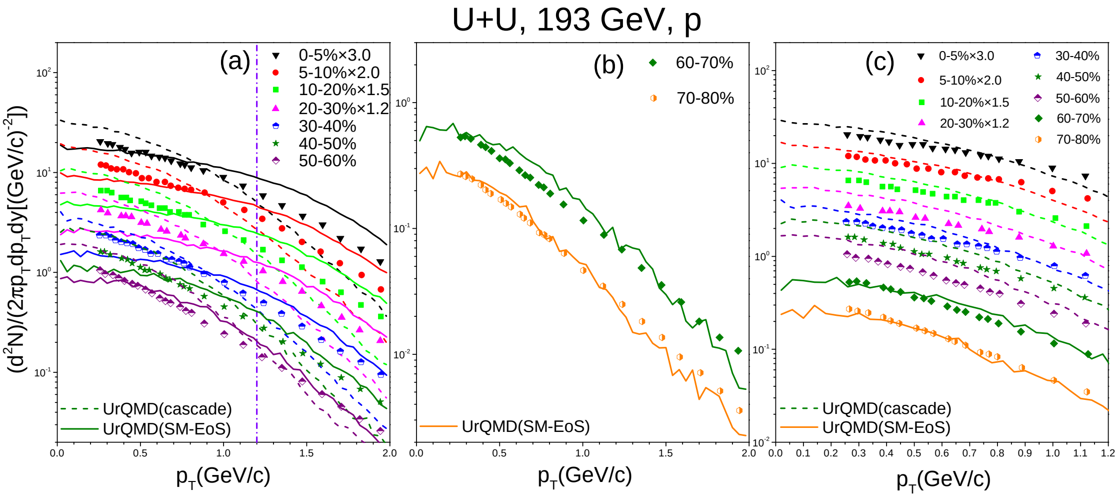

FIG. 5: Transverse momentum spectra of p are calculated at mid-rapidity ($|y| < 0.1$) in U+U collisions at $\sqrt{s_{NN}}$=193 GeV for $0-5\%$, $5-10\%$, $10-20\%$, $20-30\%$, $30-40\%$, $40-50\%$, $50-60\%$, $60-70\%$ and $70-80\%$ centralities from the cascade mode and the soft momentum dependent equation of state mode of UrQMD model. The lines denote calculations, while the symbol represents experimental data taken from the STAR Collaboration [23].

TABLE I: Values of $\langle p_T \rangle$ in GeV/c within mid-rapidity ($|y| < 0.1$) of π^+, π^-, k^+, k^-, p and $\bar{p}$ for U+U collisions at $\sqrt{s_{NN}}$=193 GeV using the UrQMD model.

Centrality	π^+	π^-	k^+	k^-	p	$\bar{p}$
0-5%	0.454 ± 0.092	0.454 ± 0.093	0.668 ± 0.037	0.667 ± 0.019	0.985 ± 0.028	1.039 ± 0.020
5-10%	0.447 ± 0.084	0.447 ± 0.085	0.652 ± 0.033	0.655 ± 0.032	0.962 ± 0.025	1.014 ± 0.018
10-20%	0.438 ± 0.073	0.438 ± 0.073	0.637 ± 0.029	0.636 ± 0.027	0.934 ± 0.022	0.982 ± 0.016
20-30%	0.426 ± 0.064	0.426 ± 0.065	0.613 ± 0.026	0.611 ± 0.043	0.816 ± 0.019	1.036 ± 0.018
30-40%	0.414 ± 0.049	0.414 ± 0.049	0.586 ± 0.019	0.584 ± 0.018	0.849 ± 0.015	0.882 ± 0.011
40-50%	0.401 ± 0.039	0.402 ± 0.039	0.559 ± 0.015	0.557 ± 0.014	0.803 ± 0.012	0.830 ± 0.009
50-60%	0.393 ± 0.031	0.393 ± 0.031	0.535 ± 0.012	0.536 ± 0.011	0.745 ± 0.009	0.764 ± 0.007
60-70%	0.419 ± 0.020	0.416 ± 0.021	0.555 ± 0.008	0.548 ± 0.007	0.766 ± 0.005	0.793 ± 0.005
70-80%	0.408 ± 0.012	0.409 ± 0.013	0.530 ± 0.005	0.526 ± 0.005	0.708 ± 0.003	0.730 ± 0.003

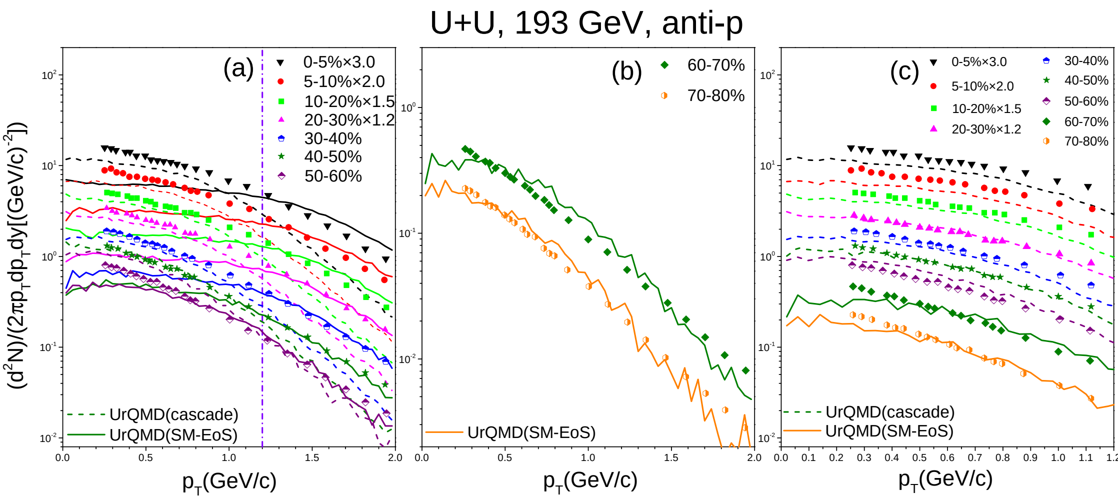

FIG. 6: Transverse momentum spectra of $\bar{p}$ are calculated at mid-rapidity ($|y| < 0.1$) in U+U collisions at $\sqrt{s_{NN}}$=193 GeV for $0-5\%$, $5-10\%$, $10-20\%$, $20-30\%$, $30-40\%$, $40-50\%$, $50-60\%$, $60-70\%$ and $70-80\%$ centralities from the cascade mode and the soft momentum dependent equation of state mode of UrQMD model. The lines denote calculations, while the symbol represents experimental data taken from the STAR Collaboration [23].

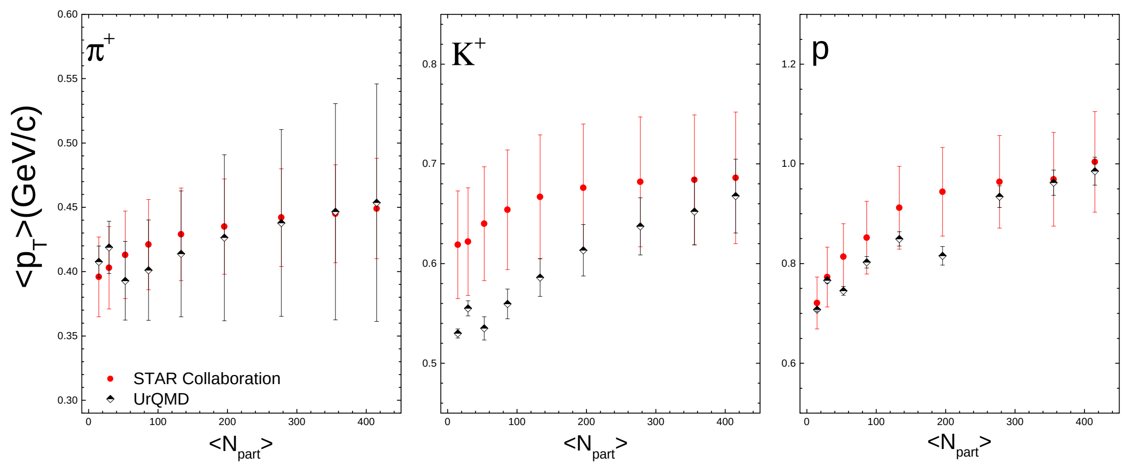

FIG. 7: $\langle p_T \rangle$ as a function of $\langle N_{part} \rangle$ at mid-rapidity ($|y| < 0.1$) of π^+, k^+ and p for U+U collisions at $\sqrt{s_{NN}}$=193 GeV. The red solid circles represent data collected by the STAR Collaboration [23]. The black diamonds are the calculation using UrQMD model.

increase slowly with the decrease of collision centrality, and they are listed in Table I.

C. Particle yields

Fig. 8 show the dN/dy as a function of $\langle N_{part}\rangle$ at mid-rapidity ($|y| < 0.1$) of π^+, k^+, p and $\bar{p}$ in U+U collisions at $\sqrt{s_{NN}}$=193 GeV. The black diamonds are the results calculated from the UrQMD model, and the red solid circles are the experimental data [23]. The values of dN/dy increase slowly with the decrease of collision centrality, and they are listed in Table II. It can be found that the theoretical results of k^+, p and $\bar{p}$ are in good agreement with the experimental data within the allowable error range, except that the π^+ mesons of peripheral collision deviate greatly from the experimental solution. This is because π mesons are produced by nucleon-nucleon interaction, nucleon resonance states and baryon intermediate states decay. The nucleon resonance states and baryon intermediate states have great influence on the yield of π mesons. In the peripheral collision, the impact of the mean field is taken into account, as it decelerates the π mesons escaping from the collision zone, resulting in a greater production of π mesons within that region. Another significant reason is that the deformation effects of the uranium nucleus have not been considered, and the definition of peripheral collision varies across different collision modes. This topic will be explored in greater detail in future research.

D. Particle ratios

Fig. 9 show π^-/π^+, k^-/k^+ and $\overline{p}/p$ as a function of $\langle N_{part}\rangle$ at midrapidity ($|y| < 0.1$) for U+U collisions at $\sqrt{s_{NN}}$=193 GeV. The black diamonds are results from the UrQMD calculations, and the red solid circles show the experimental data [23]. It is found that the experimental results can be described within the tolerance of error. For π and k, yield ratios are very close to one another and all are approximately constant. This shows that positive and negative mesons are produced in pairs. For the $\bar{p}/p$, the collision from edge to center shows a slight downward trend. This shows that the more central the collision, the stronger

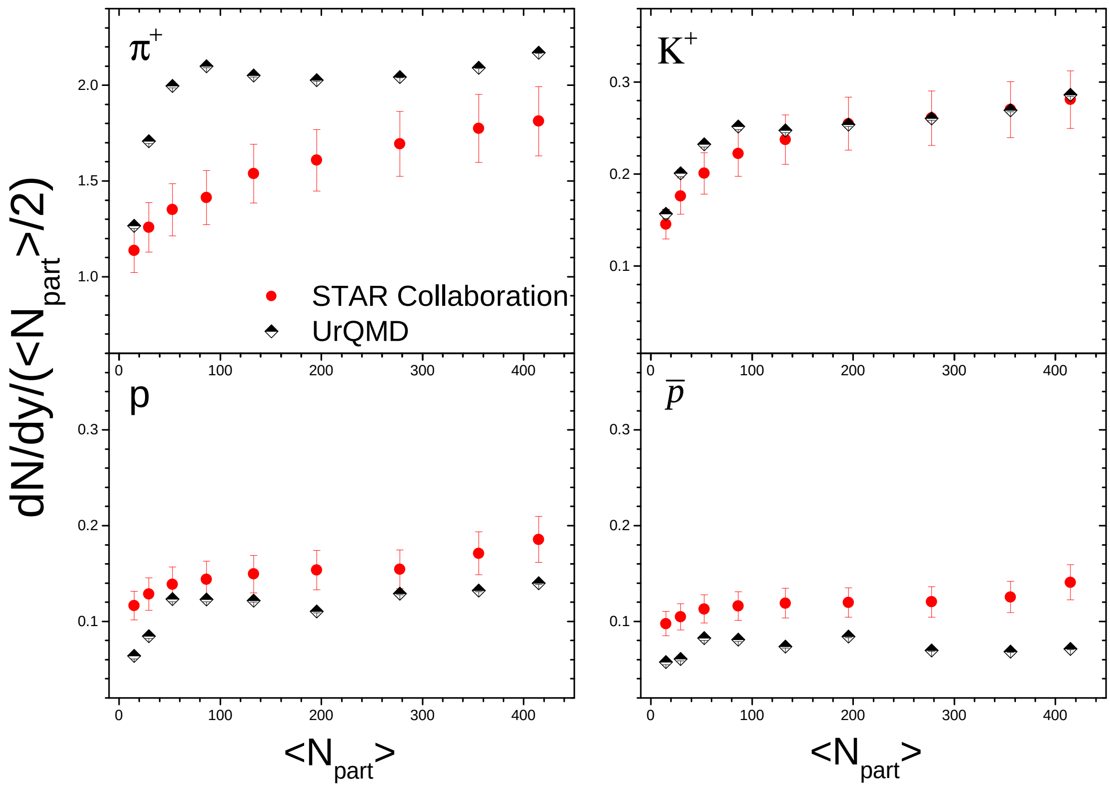

FIG. 8: dN/dy by $\langle N_{part} \rangle /2$ as a function of $\langle N_{part} \rangle$ at mid-rapidity ($|y| < 0.1$) of π^+, k^+, p and $\bar{p}$ for U+U collisions at $\sqrt{s_{NN}}$=193 GeV. The red solid circles represent experimental data taken from the STAR Collaboration [23]. The black diamonds are the calculation using UrQMD model.

the blocking effect on the proton.

IV. SUMMARY AND OUTLOOK

In summary, in the centrality classes $0-5\%$, $5-10\%$, $10-20\%$, $20-30\%$, $30-40\%$, $40-50\%$, $50-60\%$, $60-70\%$ and $70-80\%$ in U+U collisions at $\sqrt{s_{NN}}$=193 GeV, the transverse momentum spectra of $\pi^{\pm}$, $k^{\pm}$ and $p(\bar{p})$ were measured in mid-rapidity ($|y| < 0.1$). Other extracted observables from p_T specrra such as average transverse momentum ($\langle p_T \rangle$), particle yields (dN/dy) and particle ratios are also shown as functions of collision centrality. We analyzed the experimental results from the STAR Collaboration [23] using the UrQMD model and found that the U+U collision process is subregional [34], mainly because the U nucleus is the largest deformation nucleus. Due to its non-spherical symmetry, when the

TABLE II: Values of dN/dy within mid-rapidity ($|y| < 0.1$) of π^+, π^-, k^+, k^-, p and $\bar{p}$ for U+U collisions at $\sqrt{s_{NN}}$=193 GeV using the UrQMD model.

Centrality	π^+	π^-	k^+	k^-	p	$\bar{p}$
0-5%	500.23 ± 0.98	502.87 ± 0.98	66.75 ± 0.38	59.97 ± 0.36	33.37 ± 0.29	16.97 ± 0.20
5-10%	412.81 ± 0.89	415.42 ± 0.89	53.76 ± 0.34	48.97 ± 0.33	27.04 ± 0.26	14.02 ± 0.19
10-20%	315.00 ± 0.77	317.56 ± 0.77	40.62 ± 0.29	36.73 ± 0.28	20.59 ± 0.22	11.13 ± 0.17
20-30%	220.00 ± 0.64	222.89 ± 0.64	27.89 ± 0.24	25.28 ± 0.23	12.40 ± 0.17	9.47 ± 0.16
30-40%	535.00 ± 1.40	540.45 ± 1.41	18.52 ± 0.19	17.35 ± 0.19	9.32 ± 0.15	5.63 ± 0.12
40-50%	100.53 ± 0.41	101.35 ± 0.42	12.19 ± 0.15	10.98 ± 0.14	6.09 ± 0.12	4.01 ± 0.10
50-60%	58.34 ± 0.27	61.83 ± 0.28	6.87 ± 0.09	6.78 ± 0.09	3.73 ± 0.09	2.50 ± 0.07
60-70%	27.89 ± 0.19	29.51 ± 0.19	3.32 ± 0.06	3.29 ± 0.06	1.43 ± 0.04	1.03 ± 0.04
70-80%	10.34 ± 0.11	11.07 ± 0.12	1.29 ± 0.04	1.18 ± 0.04	0.54 ± 0.03	0.49 ± 0.02

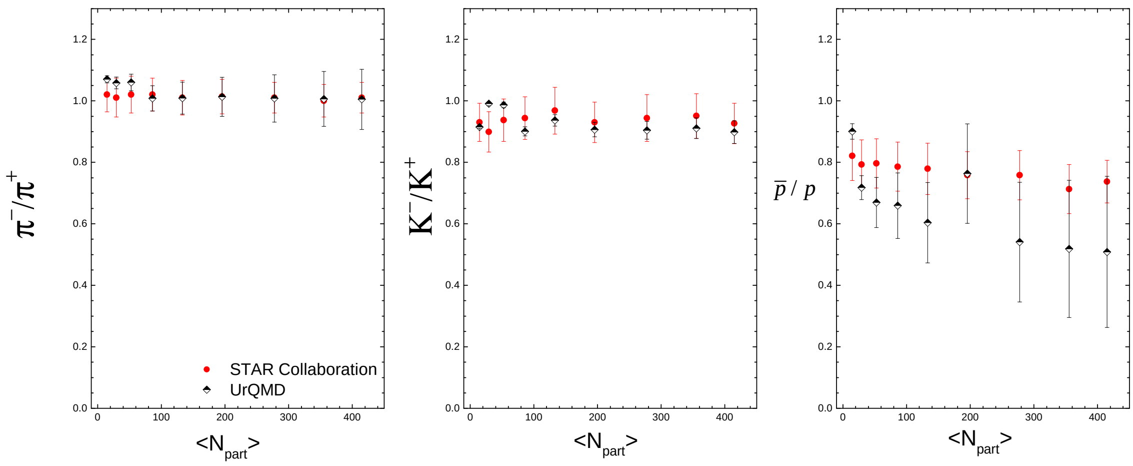

FIG. 9: π^-/π^+, k^-/k^+ and $\bar{p}/p$ as a function of $\langle N_{part} \rangle$ at mid-rapidity ($|y| < 0.1$) for U+U collisions at $\sqrt{s_{NN}}$=193 GeV. The experimental data of the STAR Collaboration [23] used in this analysis is shown as red solid circles. The black diamonds are the calculation using UrQMD model.

U+U collides along different directions, the central high-density material formed in the collision process will have different compression rates and lifetimes. Before the collision centrality is $50-60\%$, the experimental data are described well using cascade mode when

the $p_T < 1.2GeV/c$. The results are in good agreement with the experimental data using the SM-EoS mode at $p_T > 1.2GeV/c$. For the case of $60-80\%$ centrality, the SM-EoS mode describes the data better. At RHIC energy, anti-baryon to baryon yield ratios indicating pair production is the dominant mechanism of particle production. In the follow-up study, we will focus on the influence of the deformation of the U nucleus on the yield of particles at the final state of the collision.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgements

We are grateful to the C3S2 computing center in Huzhou University for calculation support. This study used computational resources provided by Institute of Marine Drugs, Guangxi University of Chinese Medicine and the special Fund for Hundred Talents Program for Universities in Guangxi (Gui2019-71). The authors acknowledge the Beijing Super Cloud Computing Center (BSCC) for providing HPC resources that have contributed to the research results reported within this paper. URL: http://www.blsc.cn/ This work was supported by the Fund for Less Developed Regions of the National Natural Science Foundation of China under Grant No.12365017, the Natural Science Foundation of Guangxi Zhuangzu Autonomous Region of China under Grant No. 2021GXNSFAA196052, the Introduction of Doctoral Starting Funds of Scientific Research of Guangxi University of Chinese Medicine under Grant No.2018BS024, and the Open Project of Guangxi Key Laboratory of Nuclear Physics and Nuclear Technology, No. NLK2020-03.

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